greater or less, according as the two mediums differ in respect of density. Thus, rays, in passing from air into glass, undergo a greater refraction, than when they pass from air into water; in both cases, however, the refracted rays approach the perpendicular. In like manner, rays passing from glass into air, undergo a greater refraction than when they pass from water into air; but in these cases, the refracted ray recedes from the perpendicular.

Finally, it must likewise be remarked, that the difference between the angle of incidence and the angle of refraction is so much greater, as the angle of incidence is greater; or, as the incident ray recedes farther from the perpendicular, the greater will be the bending or refraction of the ray. A relation between all these angles exists, and is determinable by geometry; but it is not now necessary to enter into the detail. What has been already said, is sufficient for understanding what I have farther to propose on the subject.

*22d July* 1760.

## LETTER XXXI.—REFRACTION OF RAYS OF DIFFERENT COLOURS.

YOU have seen, that when a ray of light passes obliquely from one transparent medium to another, it undergoes a bending, which is called refraction, and that the refraction depends on the obliquity of the incidence, and the density of the mediums. I must now call upon you to remark, that diversity of colours occasions, likewise, a small variety in the refraction. This arises, undoubtedly, from the circumstance, that the rays which excite in us the sensations of different colours, perform unequal numbers of vibrations in the same times, and that they

differ among themselves, in the same manner as sharper or flatter sounds do. Thus, it is observable, that rays of *red* undergo the least bending or refraction; after them come the *orange*; the *yellow*, the *green*, the *blue*, and the *violet*, follow in order; so that violet-coloured rays undergo the greatest refraction; it being always understood, that the obliquity of the incidence, and the density of the mediums, are the same. Hence, it is concluded, that rays of different colours have not the same refrangibility; that the *red* are the least, and the *violet* the most refrangible.

If then, P C (PLATE I. *Fig.* 10.) is a ray passing, for example, from *air* into *glass*; the angle of incidence being P C E, the refracted ray will approach the perpendicular C F; and if the ray be *red*, the refracted ray will be in the direction C—*red*; if it be *orange*, the refracted ray will be C—*orange*; and so of the rest, as may be seen in the figure. All these rays deviate from the line C Q, which is P C produced, toward the perpendicular C F; but the red ray deviates the least from C Q, or undergoes the least refraction, and the violet recedes the farthest from C Q, and undergoes the greatest refraction.

Now if P C is a ray of the sun, it produces at once all the coloured rays indicated in the figure; and if a piece of white paper is placed to receive them, you will in effect see all these colours; hence it is affirmed, that every ray of the sun contains at once all the simple colours. The same thing happens if P C is a ray of white, or if it proceeds from a white body. We see all the colours produced from it by refraction, whence it is concluded that white is an assemblage of all the simple colours, as we formerly showed. In truth, we have only to collect all these coloured rays into a single point, and the colour of white will be the result.

It is thus we discover what are the simple colours. Refraction determines them incontestibly. In following the order which it presents, they are these: 1. red, 2. orange, 3. yellow, 4. green, 5. blue, 6. violet.* But it must not be imagined that there are but six; for as difference of colours arises from the number of vibrations which rays perform in one and the same time, or rather the undulations which produce them, it is clear that the intermediate numbers equally give simple colours. But we want names by which to design these colours; for between *yellow* and *green*, we evidently perceive intermediate colours, for which we have no separate names.

In conformity to the same laws, are produced the colours visible in the *Rainbow.* The rays of the sun, in passing through the drops of water which float through the air, are by them reflected and refracted, and the refraction decompounds them into the simple colours. You must undoubtedly have remarked, that these colours follow each other in the same order in the rainbow, the *red, orange, yellow, green, blue,* and *violet;* but we discover in it also all the intermediate colours, as shades of one colour to another; and had we more names to distinguish these degrees, we might find more of them from the one extremity to the other. A more copious language may perhaps enable another nation actually to reckon a greater number of different colours; and another, it may be, cannot reckon so many; if, for example, it wants a term to express what we call orange. Some to these add *purple,* which we perceive at the extremity of the red, but which others comprehend under the same name with red.

| C. | D. | E. | F. | G. | A. | B. |
|---|---|---|---|---|---|---|
| Purple. | Red. | Orange. | Yellow. | Green. | Blue. | Violet. |

These colours may be compared to the notes of an octave, as I have done here, because the relations of colours, as well as those of sounds, may be expressed by numbers. There is even an appearance, that by straining the violet a little more, you may come round to a new purple, just as in rising from sound to sound, on going beyond B you come round to *c*, which is the octave above C. And as in music we give to these two notes the same name, because of their resemblance, the same thing takes place in colours, which, after having risen through the intervals of an octave, resume the same names; or, if you will, two colours, like two sounds, in which the number of vibrations in the one is precisely the double of the other, pass for the same, and bear the same name.

On this principle it was that Father *Castel,* in France, contrived a species of music of colours. He constructed a harpsichord, of which every key displayed a substance of a certain colour; and he pretended that this harpsichord, if skilfully touched, would present a most agreeable spectacle to the eye. He gave it the name of the *Ocular Harpsichord,** and you must undoubtedly have heard it talked of.

---

* When the beam of light is very small, Dr. Wollaston found that there were only *four* colours, viz. *red, yellowish-green, blue,* and *violet,* in the proportions 16, 23, 36, and 25. These proportions, however, vary with the inclination of the incident ray, and also with the nature of the refracting body, of which the prism is formed. The power of any body to produce colour by a separation of the coloured rays, is called its *dispersive power,* which does not depend upon its *refractive power.* See the *Edinburgh Encyclopædia,* Art. Optics, vol. xv. p. 485. 541.—Ed.

* An account of Father Castel's Ocular Harpsichord will be found in Dr. Brewster's *Treatise on the Kaleidoscope,* p. 131.—Ed.

For my part, painting rather seems to be that to the eye which music is to the ear; and I greatly doubt whether the representation of several shreds of cloth of different colours could be very agreeable.

*27th July* 1760.

## LETTER XXXII.—OF THE AZURE COLOUR OF THE HEAVENS.

YOU have just seen, that the cause of the visibility of objects is a motion of vibration extremely rapid, by which the minuter particles of their surfaces are agitated, and that the frequency of these vibrations determines the colour.

It is the same thing whether these particles be agitated by an intrinsic force, as in luminous bodies, or whether they receive their agitation from illumination, or from foreign rays, by which they are illumined, as in opaque bodies. The frequency or rapidity of the vibrations depends on the grossness of these particles, and on their elasticity, as that of the vibrations of a musical string depends on its thickness and degree of tension; thus, as long as the particles of a body preserve the same elasticity, they represent the same colour, as the leaves of a plant preserve a green colour as long as they are fresh; but when they begin to dry, the difference of elasticity, which then takes place, produces likewise a different colour. This subject I have already discussed. I now proceed to explain why the heavens appear to us of a blue colour in the day-time.

On observing this phenomenon with a vulgar eye, it would appear that we are surrounded by a prodigious vault of azure, as painters represent the sky on a ceiling. I have no occasion to undeceive you respecting this prejudice: a small degree of reflection is sufficient to make you comprehend that the heavens are not an azure vault, to which the stars are affixed like so many luminous studs. You are perfectly convinced that the stars are immense bodies, at inconceivable distances from us, and which move freely through a space almost void, or which is filled only by that subtile matter called ether. And I will show you that this phenomenon is to be ascribed to our atmosphere, which is not perfectly transparent.

Were it possible to rise higher and higher above the surface of the earth, the air would become gradually more and more rare, till it ceased to assist respiration, and would at length entirely cease; we should then have reached the region of pure ether. Accordingly, in proportion as we ascend on mountains, the mercury in the barometer continues to fall, because the atmosphere becomes lighter and lighter; and then likewise it is remarked, that the azure colour of the heavens becomes fainter; and were it possible to mount into pure ether, it would entirely disappear: on looking upward, we should see nothing at all, and the heavens would appear black as night; for where no ray of light can reach us, every thing wears the appearance of black.

There is good reason, then, for asking, Why the heavens appear to be blue? This phenomenon could not exist, were air a perfectly transparent medium, as ether is: in that case, we should receive from above no other rays but those of the stars: but the lustre of day-light is so great, that the feeble light of the stars is absorbed by it. You could not perceive the flame of a taper in the day-time, at any considerable distance; but that same flame, in the night, would appear very brilliant at much greater distances. This clearly proves, that we must look for the cause of the azure colour of the heavens, in the want of transparency in the air. The air is loaded with a great quantity of small particles, which are not perfectly transparent, but which, being illuminated by the rays of the sun, receive from them a motion of vibration, which produces new rays proper to these particles; or else they are opaque, and become visible to us from being illumined.

Now, the colour of these particles is blue; and this explains the phenomenon: the air contains a great quantity of small blue particles: or it may be said, that its minuter particles are bluish, but of a colour extremely delicate, and which becomes sensible to us only in an enormous mass of air. Thus, in a room, we perceive nothing of this blue; but when the bluish rays of the whole atmosphere penetrate our eyes at once, however delicate the colour of each singly, their totality may produce a very deep colour.

This is confirmed by another phenomenon, with which you must be well acquainted. If you look at a forest, from a moderate distance, it appears quite green; but in proportion as your distance increases, it acquires a bluish cast, and this gradually becomes deeper and deeper. The forests on the mountains of Hartz, which may be seen from Magdeburg, appear thence to be blue, but viewed from Halberstadt, they are green. The great extent of air between Magdeburg and these mountains, is the reason of it. However delicate or rare the bluish particles of the air may be, there is such a prodigious quantity of them in that interval, the rays of which enter into the eye at once, that they represent a tolerable deep blue *.

We remark a similar phenomenon in a fog, when the air is loaded with a great quantity of opaque particles of a whitish colour. On looking only to a small distance, you scarcely perceive the fog; but when the distance is considerable, the whitish colour becomes very perceptible; to such a degree, that it is impossible to see through it. The water of the sea appears green at a certain depth; but when you take up a small quantity, as much, for instance, as a glass will contain, it is sufficiently diaphanous, and has no sensible colour: but in a great extent, when you look toward the bottom, so many greenish rays collected produce a deep colour.

*27th July* 1760.

## LETTER XXXIII.—OF RAYS ISSUING FROM A DISTANT LUMINOUS POINT, AND OF THE VISUAL ANGLE.

As long as the rays produced by the rapid vibration of the minuter particles of a body, move in the same transparent medium, they preserve the same direction, or diffuse themselves in all directions, in straight lines. These rays may be represented by the radii of a circle, or rather of a sphere, which, issuing from a centre, proceed in straight lines to the circumference; and it is on account of this resemblance that we employ the same term *radius*, or ray, to express them, though, properly speaking, the light does not consist of lines, but of very rapid vibrations, going continually forward, in the direction of straight lines; and, for this reason, light may be considered as straight lines, issuing from a luminous point, in all directions.

Let C (PLATE I. *Fig.* 11.) be a luminous point, from which rays issue in all directions. Let two spheres be described round C, as a centre, of the one

---

* When the purest spring water is placed in a large reservoir lined with something white, its tint is invariably of a blue colour. Hence arises the blue colour of masses of transparent ice, in the glaciers of Switzerland, and the fine blue colour of the Rhone, in issuing out of the Lake of Geneva.—ED.

of which, let the great circle be *a b d e*, and of the other A B D E. The light diffused over the surface of the smaller sphere *a b d e*, will likewise occupy that of the greater sphere A B D E. The light, then, must be more faint and weak at the surface of this last, than at that of the smaller sphere *a b d e*. Hence it may be concluded, that the effect of light must be smaller, in proportion to the distance from the luminous point. If we suppose, that the radius of the greater sphere is double that of the smaller, the surface of the greater sphere will be four times as great. Since, therefore, the same quantity of light is diffused over the surface of the greater sphere, and over that of the smaller, it must follow, that light, at double the distance, is four times more faint; at thrice the distance, nine times; at a quadruple distance, sixteen times; and so on.

On applying this rule to the light of the sun, it will appear, that if the earth were removed to double the distance from the sun, the light derived from him would be rendered four times more faint; and if the sun were an hundred times further from us, his brightness would be a hundred times a hundred, that is, ten thousand times less. Supposing, then, a fixed star to be as great and as luminous as the sun, but that it was 400,000 times farther from us, its light will be 400,000 times 400,000, that is, 160,000,000,000 times more faint than that of the sun. Hence we see, that the light of a fixed star is nothing compared to that of the sun; and this is the reason that we do not see the stars in the day time; as a feebler light always disappears in presence of one much more bright. The same thing holds good with respect to candles, and all other luminous bodies, which administer less light, in proportion to their distance from us; and you must have frequently

remarked, that however strong a light may be, it is insufficient to assist us in reading a printed book, if you remove from it to any considerable distance.

There is still another circumstance closely connected with what I have just observed, namely, that the same object appears smaller to us, in proportion to its distance. A giant, at a great distance, does not appear taller than a dwarf near us. To form a clearer judgment of this, it is necessary to attend to the angles at which these objects are seen by us.

Let us suppose, then, A B (Plate I. *Fig.* 12.) to be an object, for example, a man, and that the eye looks at it from the point C. Draw from that point the straight lines A C and B C, which represent the extreme rays proceeding from the object to the eye; we call the angle formed at C, the visual angle of that object for the point C. If we look at the same object from a smaller distance, at D, the visual angle D will be undoubtedly greater: hence it is clear, that the more distant the same object is, the smaller is its visual angle; and the nearer it approaches, its visual angle becomes greater.

Astronomers measure very accurately the angles under which we see the heavenly bodies; and they have found, that the visual angle of the sun is somewhat more than half a degree. If the sun were twice as far from us, this angle would be reduced to the half; and then it will not seem surprising that it should furnish us four times less light. And if the sun were 400 times farther off, his visual angle would become so many miles less, and then that luminary would appear no greater than a star. We must, therefore, carefully distinguish the apparent greatness of any object from its real greatness. The first is always an angle greater or less, according as the object is nearer or more distant. Thus the apparent greatness of the sun, is an angle of about half a degree, whereas his real magnitude far surpasses that of the earth; for the sun being a globe, his diameter is estimated to be about 790,000 English miles, while the diameter of the earth is only 7912 English miles.

*29th July* 1760.

## LETTER XXXIV.—OF THE ASSISTANCE WHICH JUDGMENT LENDS TO VISION.

WHAT I have now submitted to you on the phenomenon of vision, belongs to optics, which is a branch of mixed mathematics, and which likewise holds a considerable rank in physics. Beside colours, the nature of which I have endeavoured to explain, it is the business of optics to treat of the manner in which vision is performed, and of the different angles under which objects are seen.

You must have already remarked, that the same object may be viewed, sometimes under a greater visual angle, sometimes under a smaller, as it is less or more distant from us. I say farther, that a small object may be viewed under the same angle as a great one, when the former is very near, and the latter very distant. A small dish may be placed before the eye in such a manner, as to cover the whole body of the sun; and, in reality, a plate of half a foot diameter, at the distance of 54 feet, exactly covers the sun, and is seen under the same angle; and yet what a prodigious difference is there between the size of a plate and that of the sun: The full moon appears to us under nearly the same visual angle as the sun, and of consequence, nearly as great, though really much smaller; but it is to be considered, that the sun is almost 400 times more remote from us than the moon.

The visual angle is a point of so much the more importance in optics, that the images of the objects which paint themselves on the bottom of the eye, depend upon it. The greater or less the visual angle is, the greater or less they (the objects) are great or little. And as we see objects out of ourselves, only so far as their images are painted on the bottom of the eye, they constitute the immediate object of vision or sensation. One of these images, therefore, leads us to the knowledge only of three things. First, its figure and its colours conduct to the conclusion, that there is, out of us, a similar object, of such a figure, and such a colour. Secondly, its magnitude discovers the visual angle under which the object appears to us; and, finally, its place on the bottom of the eye makes us sensible of the direction of the external object, relatively to us, or that in which the rays emitted from it reach our eyes.

In these three particulars consists the phenomenon of vision; and we only perceive, 1st, the figure and colours; 2dly, the visual angle, or the apparent magnitude; and, 3dly, the direction, or the place in which we conclude that the object exists. Vision, then, discovers to us nothing respecting either the real magnitude of objects, or their distances. Though we frequently imagine, that we can determine by the eye the magnitude and distance of an object, this is not an act of vision, but of the understanding. The other senses, and habits of long standing, enable us to calculate at what distance an object is from us. But this faculty extends only to objects at no great distance. Whenever their distance becomes considerable, our judgment cannot exercise itself with certainty; and if sometimes we venture to hazard a decision, it is generally very remote from the truth.

Thus, no one can pretend to say that he sees the magnitude or the distance of the moon; and when the vulgar imagine they can judge of the first, by considering it as equal to that of the terrestrial bodies which are seen under the same angle, it is not by vision they are deceived, but by their judgment, which they want to apply to an object far beyond their reach. It is certain, therefore, that the eyes alone can determine nothing respecting the distance and magnitude of objects.

To this subject may be referred the very remarkable case of a man born blind, who obtained sight, by means of an operation, at an advanced period of life.* This person was at first dazzled; he could distinguish nothing as to the magnitude and distance of objects. Every thing appeared so near, that he wanted to handle them. A considerable time, and long practice, were requisite to bring him to the real use of sight. He was under the necessity of serving a long apprenticeship, such as we perform during the term of childhood, and of which we afterwards preserve no recollection.

This it is which instructed us, that an object appears to us so much the more clear and distinct as it is nearer; and reciprocally, than an object which appears clear and distinct is near; and when it appears obscure and indistinct, that it is at a distance. It is thus that painters, by weakening the tints of the objects which they wish to appear remote, and strengthening those which they would represent as nearer, are enabled to determine our judgment, conformably to the effect which they mean to produce. And they succeed so perfectly, that we consider some of the objects represented in painting as more distant than others—an illusion which could not take place, if vision discovered to us the real distance and magnitude of objects.

1st *August* 1760.

---

* This was the young man, blind from cataract, on whom our countryman *Chesselden* performed the operation of couching. An account of this interesting case, which is so often referred to, will be found in the *Philosophical Transactions* for 1728, vol. xxxv. p. 447.—Ed.

## LETTER XXXV.—EXPLANATION OF CERTAIN PHENOMENA RELATIVE TO OPTICS.

You have just seen, that vision alone discovers to us nothing respecting either the real magnitude or the distance of objects; and that all we imagine we see, whether as to the distance or magnitude of any object, is the effect of judgment. We must carefully distinguish that which the senses represent to us, from what judgment adds, in which we frequently deceive ourselves. Many philosophers, who have declaimed against the accuracy of the senses, and who meant thence to infer the uncertainty of all human knowledge, have confounded the proper representations of our senses with judgment.

This is their mode of reasoning: We see the sun no bigger than a trencher, though it be infinitely greater; therefore the sense of seeing deceives us; therefore all our senses deceive us; at least, we cannot depend on them; therefore, all the knowledge we acquire by means of the senses, is uncertain, and probably false: We, therefore, know nothing. Such is the reasoning of these sceptics, who boast so vaingloriously of their ingenuity; though there be nothing so easy as to say, that every thing is uncertain; and the greatest dunce may make a shining figure in this sublime philosophy. But it is absolutely false, that the sight represents to us the sun no bigger than a pewter plate; it determines nothing whatever respecting his magnitude; it is our judgment alone that deceives us. When the objects, however, are not very distant, we can pronounce with tolerable exactness on their dimensions and distances; and the other senses joined to the degree of clearness with which we see these same objects, render our judgments sufficiently certain. Now, as soon as we have the idea of the distance of an object, we form to ourselves, likewise, that of its real magnitude, knowing that it depends on that distance. Hence, the more distant we reckon an object to be, the greater we conclude is its magnitude; and reciprocally, the nearer we conclude it is, the smaller we suppose it. We, of course, frequently take one body for another of much greater magnitude, when a suspension of judgment prevents our taking distance into the account. The reason is, that a very large body may be seen at a great distance, under the same angle as a small object placed near us.

There is another phenomenon well known to every one, and which has given occasion to many disputes among the learned, and which it is now perfectly easy to explain. The full moon appears to every eye at the time of her rising to be much greater than when she has got to a considerable height above the horizon, though the visual angle of the apparent magnitude be the same. The sun, too, at the time of rising and setting, appears to every one greater than at noon. What then is the foundation of this judgment, so universal, and so false? It is undoubtedly because we judge the sun and the moon in the horizon to be at a greater distance from us than when they have got to a considerable height.

But how come we to form such a judgment? The common answer is, that when the sun and the moon are in the horizon, we perceive a great many objects between them and us which seem to increase their distance; whereas when the sun and moon have risen to a great height, we perceive nothing between them and us, and therefore conclude that they are nearer. I know not whether this explanation will be satisfactory. It may be objected, that an empty apartment appears greater than one completely furnished, though the size be exactly the same; several intervening objects, therefore, do not always lead us to imagine that one more remote is at a greater distance than is really the case. I flatter myself that the following solution will be deemed more natural, and better founded.

Let the circle A (Plate I. *Fig.* 13.) represent the earth, and the dotted circle the atmosphere or air with which the earth is surrounded; suppose yourself stationed at the point A, if the moon is in the horizon, the rays will reach you in the direction of the line B A; but in her extreme height, the rays will descend in the line C A. In the first case the rays pass through the greater space B A, and in the second case through the smaller space C A. Now you will please to recollect, that the rays of light which pass through a transparent medium have their force diminished in proportion to the length of the passage. The atmosphere or air, then, being a transparent medium, the ray B A must in its passage lose much more of its force than the ray C A. Hence it follows in general, that all the celestial bodies appear much less brilliant in the horizon than when fully risen and elevated. We are able to look directly even at the sun when he is in the horizon; but when once he has gained a certain height, the eye is constrained to shrink from his lustre.

I conclude from this that the moon, too, appears less brilliant in the horizon than when elevated.*

---

* A more complete explanation of this phenomenon will be found in Dr. Smith's *Optics*, vol. i. p. 63. He shows that the apparent figure of the sky resembles B F E D (Plate I. *Fig.* 32.), being much less than a

Now you will recollect what I said a little above, in speaking of effect in painting, that the same object appears to us more distant when its light is weakened: the moon, then, being in the horizon, must appear more distant than at any point of elevation. The consequence is obvious; as we judge the distance of the moon greater in the horizon, we must likewise judge her magnitude greater. And in general all the stars, when near the horizon, appear to us greater, because their apparent distance is greater.

*3d August* 1760.

## LETTER XXXVI.—OF SHADOW.

I HAVE endeavoured to explain almost all that is usually treated of in optics. All that remains is to speak of shadow. You already know too well what is meant by *shade* or *shadow*, to render it necessary for me to dwell long on the subject. Shadow always supposes two things: a luminous body, and an opaque body, which does not transmit the rays of light. The opaque body, then, prevents the rays of

---

hemisphere; and considering that the moon at *m n* subtends an angle *m* O *n* equal to the angle *o* O *p*, which it subtends at *o p*, he concludes that the moon must appear much larger at *o p* than at *m n*, in consequence of its being supposed to be at a much greater distance. When a star seemed to be half way between the horizon and the zenith, Dr. Smith found its real altitude to be only 23°; and upon this principle he constructed the following table:—

| Sun or Moon's altitude, in degrees. | Apparent Diameters, or Distances. |
|---|---|
| 0 | 100 |
| 15 | 68 |
| 30 | 50 |
| 45 | 40 |
| 60 | 34 |
| 75 | 31 |
| 90 | 30 |

ED.

a luminous body from getting behind it, and the space which the rays cannot reach from this interception, is called the shadow of the opaque body; or, what comes to the same thing, shadow includes all that space in which the luminous body is not to be seen, because the opaque body obstructs its rays.

Let A (PLATE I. *Fig.* 14.) be a luminous point, and B C D E an opaque body. Draw the extreme rays A B M, A D N, touching the opaque body. It is evident that no ray of light proceeding from A can penetrate into the space M B E D N; and in whatever point within that space the eye may be placed, at O, for example, it will not see the luminous body. This space is the shadow of the opaque body; and we see that it is continually increasing, and may extend to infinity. But if the body from which the rays proceed be itself of great magnitude, the determination of the shadow is somewhat different. There are three cases which demand consideration; the first is, when the luminous body is less than the opaque; the second, when they are equal; and the third, when the luminous body is the greater. The first case is that which we have now been considering, in which the light is smaller than the opaque body.

The second is represented in (PLATE I. *Fig* 15.), where the luminous body A is of the same magnitude with the opaque body B C E D. If you draw the extreme rays A B M, A E N, the space M B E N will be shaded, and through the whole of that space it will be impossible to see the luminous body. You see likewise that the lines B M and E N are parallel, and that the shadow extends to infinity, always preserving the same breadth.

The third case is exhibited in (PLATE I. *Fig.* 16), where the luminous body A A is greater than the opaque body B C E D. The extreme rays touching the opaque body in B and E, if produced, will meet in the point O, and the space of the shadow B O E becomes finite, and terminates in O. The shade in this case is termed conical. It is only into this space that the light has no admission, and in which it is impossible to see the luminous body. To this third case belong the shadows of the celestial bodies, which are much smaller than the luminous body which enlightens them, namely, the sun.

We have here, then, another display of the Creator's wisdom. For if the sun were smaller than the planets, their shadows would not be terminated, but extend to infinity, which would deprive immense spaces of the benefit of the sun's light. But the magnitude of that luminary surpassing by so many times that of the planets, their shadows are contracted to very narrow bounds, from which alone the light of the sun is excluded.

It is thus that the earth and the moon project their conical shadows; and the moon may occasionally plunge into the shadow of the earth either partially or totally. When this takes place, we say the moon is eclipsed, either wholly or in part. In the former case we call it a total eclipse of the moon; in the other, a partial eclipse. The moon, likewise, projects her shadow, but it is smaller than that of the earth. It may happen, however, that the shadow of the moon should extend as far as to the earth; and then those who are involved in that shadow, undergo an eclipse of the sun. An eclipse of the sun, then, takes place when the moon, interposing, prevents our seeing the sun wholly, or in part. We see not the sun by night, though there be no eclipse; but we are then in the shadow of the earth, which causes our greatest obscurity.

Hitherto we have considered only the cases in which the rays of light are transmitted in straight lines, which is the professed object of optics. But

it has been already remarked, that the rays of light are sometimes reflected, and sometimes broken or refracted. You will recollect, that when the rays fall on a well-polished surface, such as a mirror, they are reflected from that surface; and when they pass from one transparent medium to another, they undergo refraction, and are in some sense broken. Hence arise two other sciences. That which considers vision in reference to reflected rays, is called *Catoptrics;* and that which has for its object vision, in reference to broken or refracted rays, is termed *Dioptrics.* Optics treat of vision relatively to direct rays of light. I shall present you with a summary of these two sciences, catoptrics and dioptrics, as they disclose phenomena which are every day presenting themselves, and of which it is of importance to investigate the causes and the properties. Every thing relating to the subject of vision is, beyond contradiction, an object highly worthy of exciting curiosity, and of engaging attention.

*5th August* 1760.

## LETTER XXXVII.—OF CATOPTRICS, AND THE REFLECTION OF RAYS FROM PLAIN MIRRORS.

CATOPTRICS treat of vision relatively to reflected rays. When rays of light fall on a well-polished surface, they are reflected in such a manner that the angles on all sides are equal among themselves.

To set this in a clear light, let A B (PLATE I. *Fig.* 17.) be the surface of a common mirror, and P a luminous point, whose rays P Q, P M, P *m*, fall upon the mirror. Of all these rays, let P Q be that which falls perpendicularly on the mirror, and which has this particular and remarkable property, that it is reflected upon itself in the direction of Q P; just as on a billiard table, when the ball is struck perpendicularly against the ledge, it is repelled in the selfsame direction. But every other ray, as P M, is reflected in the line M N, in such a manner, as to make the angle A M N equal to the angle B M P; in which it is to be remarked, that the ray P M is named the incident ray, and M N the reflected ray. In like manner, to the incident ray P *m*, will correspond the reflected ray *m n*; and, consequently, because of the reflection, the ray P M is continued in the direction of the line M N, and the ray P *m* in the direction of *m n*, so that we have the angle A M N, equal to B M P, and the angle A *m n*, equal to the angle B *m* P. This property is thus enounced: *The angle of reflection is always equal to the angle of incidence.*

I have already taken notice of this striking property; but my design, at present, is to show what the phenomena in vision are, which result from it. First, it is evident, that an eye, placed at N, will receive from the luminous point P, the reflected ray M N; thus the ray which excites in that eye the sensation of the body from whence it proceeded, comes in the direction M N, just as if the object P were in some point of that line; hence it follows that the eye must see the object P in the direction N M.

In order the more clearly to elucidate this fact, we must have recourse to geometry; and you will recollect with pleasure the propositions on which the following reasoning is founded. Let the perpendicular ray P Q be produced on the other side the mirror to R, so that Q R shall be equal to P Q; I will show you that all the reflected rays, M N, and *m n* being produced behind the mirror, must meet in that point. For, taking the two triangles P Q M and R Q M, they have first the side M Q common to both; then the side Q R was made equal to the side P Q; and, finally, the angle P Q M being a right angle, its adjacent angle R Q M must likewise be a right angle (Euclid's Elements, Book I. Prop. 13.) Therefore these two triangles, having each an equal angle contained by two equal sides, shall be every way equal (Euclid, Book I. Prop. 4.), and consequently the angle P M Q equal to the angle R M Q. But the angle A M N, and the angle R M Q, being vertical, are equal to each other (Euclid, Book I. Prop. 15.), therefore also the angle A M N shall be equal to the angle P M Q; that is, the angle of reflection shall be equal to the angle of incidence.

In the same manner it is demonstrated, that the reflected ray *m n* being produced, would likewise pass through the point R, and consequently produce in the eye the same effect as if the object P were actually placed behind the mirror at R, this point being in the perpendicular P Q R, at the same distance as P from the surface of the mirror, but on different sides. This will enable you to comprehend clearly why mirrors represent objects as if they were behind them; and why we judge that these objects are placed as far behind the surface of the mirror as they really are before it. It is thus that the mirror transports objects into another place, without changing their appearance. To distinguish in the mirror that apparent object from the real, we name the apparent object the image, and we say that the images represented by reflected rays are behind the mirror. This denomination serves to distinguish real objects from the images of them represented in mirrors; and the images which we see in mirrors are perfectly equal and similar to the objects, with this exception, that what in the object is on the left appears in the image on the right, and reciprocally. Thus a person wearing his sword on the left side, appears with it in the mirror on his right.

From what has been said, it is always easy to settle the image of any object whatever behind the mirror.

For A B (Plate I. *Fig.* 18.) being a mirror, and E F an object, say an arrow: draw from the points E and F the perpendiculars E G and F H, to the surface of the mirror, and produce these to *e* and *f*, so that E G shall be equal to *e* G, and F H to *f* H, *e f* will be the image sought, which will be equal to the object E F, because the quadrilateral figure G *e f* H is in all respects equal to the quadrilateral figure G E F H. It must be still farther remarked, that were you even to cut off from the mirror a part, as C B, and A C was the mirror, the image *e f* would not be changed. And consequently when the mirror is not sufficiently large to admit the falling of the perpendiculars E G and F H upon it, we must suppose the plane of the mirror to be extended, as we produce lines in geometry when we want to let fall perpendiculars upon them. What I have said respects only common mirrors, whose surface is perfectly plain. Convex and concave mirrors produce different effects.

*7th August* 1760.

## Letter XXXVIII.—Reflection of Rays from Convex and Concave Mirrors. Burning Mirrors.

Every thing relating to the reflection of rays is reduced, as you have seen, to two things; the one of which is the place of the image which the reflected rays represent; and the other the relation of the image to the object. In ordinary or plain mirrors, the image of the object is behind the mirror, at a distance equal to that of the object before the mirror, and it is equal and similar to the object. To both of these circumstances we must attend when the mirror is not plain; but when its surface is convex or concave; for in either case the image is, for the most part, strangely disfigured. You must frequently have remarked that on presenting any object before a spoon very highly polished, you see its image greatly disfigured, whether reflected from its interior surface, which is concave, or from its exterior, which is convex.

A globe of silver, finely polished, represents objects with sufficient accuracy, but in miniature. If the interior surface of the globe is well polished, objects appear upon it magnified; provided always that they are not too distant. For the same objects may likewise appear smaller and inverted, if they are removed far from the mirror. There is no occasion to take a whole globe; any part of its surface whatever produces the same effect. These mirrors are denominated spherical; and there are two sorts of them. The one is convex and the other concave, according as they are taken on the exterior or interior surface of the sphere. They are compounded of various metals, susceptible of a fine polish; whereas plain mirrors are made of a plate of glass, and covered on one side with a preparation of mercury, designed to stop the passage of the rays, and to reflect them. I begin with convex mirrors.

Let A C B (Plate I. *Fig.* 19.) be a mirror, the segment of a sphere, whose centre is G. If you place before this mirror an object E, at a great distance, its image will appear behind the mirror, at the point D, the middle point of the radius of the sphere C G; and the magnitude of this image will be to that of the object in the relation of the lines C D and C E: it will therefore be in this case much smaller than the object, as the line C D is in effect much smaller than the line C E. If the object E approaches to the mirror, so likewise will its image. This is all demonstrable on geometrical principles, by supposing that any incident ray whatever, say E M, is reflected in the direction of M N, so that the angle B M N may be equal to the angle C M E. Thus, when the eye is at N, receiving the reflected ray M N, it will see the object E, according to that direction, and will observe it in the mirror at the point D; or, in other words, D will be the image of the object placed at E, but smaller. It is likewise easy to see, that the smaller the sphere is, of which the mirror is a segment, the more likewise is the image diminished.

I proceed to concave mirrors, the use of which is very common on many occasions. Let A C B (Plate I. *Fig.* 20.) be a mirror, forming part of a sphere, whose centre is G, and G C a radius. Let us suppose an object E very distant from the mirror, its image will appear before the mirror at D, the middle point of the radius C G; for any ray of light whatever, E M, from the object E, falling on the surface of the mirror at the point M, will be reflected thence in such a manner as to pass through the point D; and when the eye is placed at N, it will see the object at D; but this image will be to the object in the ratio of C D to C E, and consequently in this case smaller than it. And when you bring the object nearer to the mirror, the image retires; the object being placed even at the centre G, the image is there likewise. If you bring the object still forward to D, the image will retire infinitely beyond E. But if the object be placed still farther forward, between C and D, the image will fall behind the mirror, and appear greater than the object.

When you look at yourself in such a mirror, at some point between D and C, your face will appear frightfully large. This is explained by the nature of reflection, in virtue of which the angle of incidence E M A is always equal to the angle of reflection C M N. To this species must be referred burning mirrors, and every concave mirror may be employed to burn. This remarkable property merits a more particular explanation.

Let A B C (Plate I. *Fig.* 21.) be a concave mirror, whose centre is G, and instead of the object, let the sun be at E; his reflected rays will represent the image of the sun at D, the middle point between C and G. Now, the magnitude of this image will be determined by the extreme rays S C, S C. This image of the sun will be accordingly very small; and as all the rays of the sun which fall on the mirror A B C are reflected in this image, they will be collected there, and will have so much more force, as the image D is smaller than the surface of the mirror. But the rays of the sun are endowed with the property of heating the bodies on which they fall, as well as that of illuminating them; hence it follows, that there must be at D a great degree of heat; and when the mirror is sufficiently large, this heat may become stronger than the most ardent fire. In fact, by means of such a mirror you may burn in an instant any combustible body, and even melt metals of every kind. It is the image of the sun alone which produces these surprising effects. This image is usually denominated the focus of the mirror; it falls always in the middle point of the radius C G, between the mirror and its centre G.

You must carefully distinguish *burning mirrors* from *burning glasses*, of which I shall give some account in my next letter.

*9th August* 1760.

## LETTER XXXIX.—OF DIOPTRICS.

HAVING explained the principal phenomena of *Catoptrics*, which result from the reflection of the rays of light, I proceed to treat of *Dioptrics*, whose object is to unfold the phenomena of the refraction of rays, which takes place when they pass through different transparent mediums. A ray of light does not pursue the same straight line, unless it continues its progress through the same medium. As soon as it enters another transparent medium, it changes its direction more or less, according as it falls upon it more or less obliquely. There is only one case in which it pursues a rectilinear course, namely, when it enters the other medium perpendicularly.

The instruments principally to be considered in dioptrics, are the glasses employed in the construction of telescopes and microscopes. These glasses are of a circular form, but with two faces. Every thing relating to them is reducible to the figure of these two faces, which may be plain, or convex, or concave. Their convexity, or concavity, is always equal to that of a sphere, of which the radius must be known, it being considered as the measure of the curve of those surfaces. This being laid down, we shall have several kinds of dioptric glasses.

The first species, No. I. (PLATE I. *Fig.* 22.), is that whose two faces are plain. By cutting a circular piece out of a plate of glass of equal thickness, we shall have one of this species, which makes no change on objects either as to magnitude or distance. Glass No. II. has one of its surfaces plain, and the other convex; and such are termed *plano-convex.* The third species, No. III., has one face plain, and the other concave; and these are called *plano-concave.* The fourth, No. IV., has two convex surfaces; and is called *double-convex.* No. V. has two concave surfaces, and is called *double-concave.* The species Nos. VI. VII. have one surface convex, and the other concave; and we give them the name of *meniscus.* All these lenses are reducible to two classes; the one containing those in which convexity prevails, as Nos. II. IV. VI.; in the other, concavity is predominant, namely, Nos. III. V. VII. The former class is simply denominated convex, and the latter concave. These two classes are distinguished by the following property.

Let A B (PLATE I. *Fig.* 23.) be a convex glass, exposed to a very distant object, E F, whose rays, G A, G C, G B, fall on the glass, and passing through it, undergo a refraction, which will take place in such a manner, that the rays proceeding from the point G shall meet on the other side of the glass in the point *g*. The same thing will happen to the rays which proceed from every point of the object. By this alteration all the refracted rays, A *l*, B *m*, C *n*, will pursue the same direction as if the object were at *e*, *g*, *f*, and inverted; and it will appear as many times smaller as the distance C *g* shall be contained in the distance C G. We say, then, that such a glass represents the object E F behind it at *e f*; and this representation is called the *image*, which is consequently inverted, and is, with the object itself, in the ratio of the distances of the glass from the image, and of the glass from the object.

It is clear, then, that if the sun were the object, the image represented at *e f* would be that of the sun; though very small, it will be so brilliant as to dazzle the eye, for all the rays which pass through the glass meet in this image, and they exercise their double power of giving light and heat. The heat there is nearly as many times greater as the surface of the glass exceeds in magnitude the image of the sun, named its *focus*, from which, if the glass be very great, you may produce the greatest effects of heat. Combustible substances placed in the focus of such a glass, are instantly consumed. Metals are melted, and even vitrified by it; and other effects are produced far beyond the reach of the most active and intense fire.

The reason is the same as in the case of burning mirrors. In both, the rays of the sun, diffused over the whole surface of the mirror or glass, are collected in the small space of the sun's image. The only difference is, that in mirrors the rays are collected by reflection, and in glasses by refraction. Such is the effect of convex glasses, which are thicker in the middle than at the extremities, and which I have represented in Nos. II. IV. and VI. Those represented in Nos. III. V. and VII. are thicker at the extremities than at the middle; and being all comprehended under the term concave, produce a contrary effect.

Let A C B (Plate I. *Fig.* 24.) be a glass of this form. If you expose to it, at a great distance, the object E G F, the rays G A, G C, G B, proceeding from the point G, will undergo a refraction, on leaving the glass in the direction of A *l*, C *m*, and B *n*, as if they had issued from the point *g*; and an eye placed behind the glass, at *m*, for example, will see the object just as if it were placed at *e g f*, and in a situation similar to that in which it is at the point G, but as many times smaller as the distance C G exceeds the distance G *g*. Convex glasses, then, represent the image of a very distant object behind them, concave glasses represent it before them; the former represent it inverted, and the latter in its real situation. In both the image is as many times smaller as the distance of the object from

the glass exceeds that of the glass from the image. On this property of glasses is founded the construction of telescopes, spectacles, and microscopes.

11*th August* 1760.

## LETTER XL.—CONTINUATION. OF BURNING GLASSES, AND THEIR FOCUS.

CONVEX glasses furnish some farther remarks, which I beg leave to lay before you. I speak here of those glasses in general which are thicker in the middle than at the extremities; whether both surfaces be convex, or one plain and the other convex; or, finally, one concave and the other convex; provided, however, that the convexity exceed the concavity, or that the thickness be greater at the middle than at the extremities. It is farther supposed, that the glasses have a spherical figure.

They have first this property, that being exposed to the sun, they present behind them a focus, which is the image of that luminary, and which is endowed, like it, with the property of illuminating and burning. The reason is, that all the rays issuing from the sun, and falling on this surface, are collected by the refraction of the glass into a single point. The same thing happens, whatever be the object exposed to such a glass; it always presents the image of it, which you see instead of the object itself. The following figure will render what I have said more intelligible.

Let A B C D (Plate I. *Fig.* 25.) be a convex glass, before which is placed an object E G F, of which it will be sufficient to consider the three points E, G, F. The rays which, from the point E, fall upon the glass, are contained in the space A E B; and are all collected in the space A *e* B by refrac-